A SIMULATION OF FILM COOLING IN THE LEADING EDGE REGION OF A TURBINE BLADE (TRENCH EFFECT ON FILM EFFECTIVENESS FROM CYLINDER IN CROSSFLOW)

MOHAMAD RASIDI BIN PAIRAN

A project report submitted in partial fulfillment
of the requirement for the award of the
Degree of Master of Mechanical Engineering

Faculty of Mechanical and Manufacturing Engineering
University Tun Hussein Onn Malaysia

DECEMBER 2012

ABSTRACT

Film cooling is one of the cooling system techniques applied to the turbine blade. Gas turbine use film cooling technique to protect turbine blade from expose directly to a hot gas to avoid the blade from defect. The focus of this investigation is to investigate the effect of embedded three difference depth of trench at cooling holes geometry to the film cooling effectiveness. Comparisons are made under blowing ratio 1.0, 1.25, 1.5 and 2.0. Three configuration leading edge with depth Case A (0.0125D), Case B (0.0350D) and Case C (0.713D) were compared to leading edge without trench. Result shows that as blowing ratio increased from 1.0 to 1.25, the film cooling effectiveness is increase for leading edge without trench and also for all cases. However when the blowing ratio is increase to 1.5, film cooling effectiveness is decrease for all cases. Meanwhile for blowing ratio 2.0, the result shows the effect of depth is too small for all the cases. Overall the Case B with blowing ratio 1.25 has the best film cooling effectiveness with significant improvement compared to leading edge without trench and with trench Case A and Case C.

ABSTRAK

Teknik filem penyejukkan adalah satu teknik yang digunakan untuk menyejukkan enjin gas turbin. Teknik ini berfungsi untuk mengelakkan bilah turbin daripada terdedah secara langsung terhadap gas panas yang boleh menyebabkan kerosakan. Fokus kajian ini dijalankan adalah untuk mengkaji kesan kedalaman parit yang berbeza kepada keberkesanan filem penyejukkan. Perbandingan dilakukan pada nisbah tiupan 1.0, 1.25, 1.5 dan 2.0. Tiga model berdasarkan kes kedalaman parit yang berbeza iaitu Kes A (0.0125D), kes B (0.0350D) dan Kes C (0.713D) telah dianalisa. Ketiga-tiga model ini telah dilakukan perbandingan terhadap bilah turbin biasa. Hasil kajian menunjukkan peningkatan nisbah tiupan daripada 1.0 kepada 1.25 dapat meningkatkan kesan penyejukkan kepada semua jenis model. Walaupun demikian, apabila nisbah tiupan ditingkatkan kepada 1.5, kesan penyejukkan menurun. Sementara itu, untuk nisbah tiupan 2.0, semua kes menunjukkan kesan parit adalah terlalu sedikit terhadap keberkesanan teknik filem penyejukan. Secara keseluruhannya, pada nisbah tiupan 1.25, Kes B menunjukkan kesan peningkatan filem penyejukkan yang terbaik berbanding Kes A dan Kes C.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLE

NOMENCLATURE

BR	-	Blowing Ratio
D	-	Diameter (10D)
k-ω	-	k-omega
K	-	Temperature (Kelvin)
Re_m	-	Reynolds Number
T	-	Temperature
Ux_i	-	Local numerical averaged effectiveness
α	-	Hole axis angle from the stagnation line
σ	-	Standard deviation
ρ	-	Density
∞	-	Main stream
ñ	-	Averaged film effectiveness
V	-	Velocity
SST	-	Shear Stress Transport
CFD	-	Computational Fluid Dynamic
TBC	-	Thermal Barrier Coating
3D	-	Three Dimensional

Subscripts

Aw	-	Adiabatic wall
c	-	Cooling air
d	-	Diameter coolant hole (d=8mm)
lat	-	Lateral averaged
m	-	Number of cells
n	-	Number of data

LIST OF APPENDICES

CHAPTER I

INTRODUCTION

1.1 Introduction

Gas turbines engines with high inlet temperatures will produce high performance of turbine engines. Improvement by improvement has been done continuously by a researcher to increasing turbine inlet temperature thus produce turbine engine with high performance. Since 1940s cooling studies were introduced and many investigations were carried on in the 1950s. Around 1960, turbine cooling was first used in a commercial aircraft engine. Since that time, there has been a very rapid rise in turbine inlet temperatures, which has placed an even greater emphasis on turbine cooling. Year 1950s to 1980s. Figure 1.1 illustrates this trend. The utilization high inlet temperature of gas turbine is increased. Figure 1.2 shows the trend in improvements in rotor blade materials. As can be seen, materials improvements have played and will continue to play an important part in the increasing turbine inlet temperature trend [1].

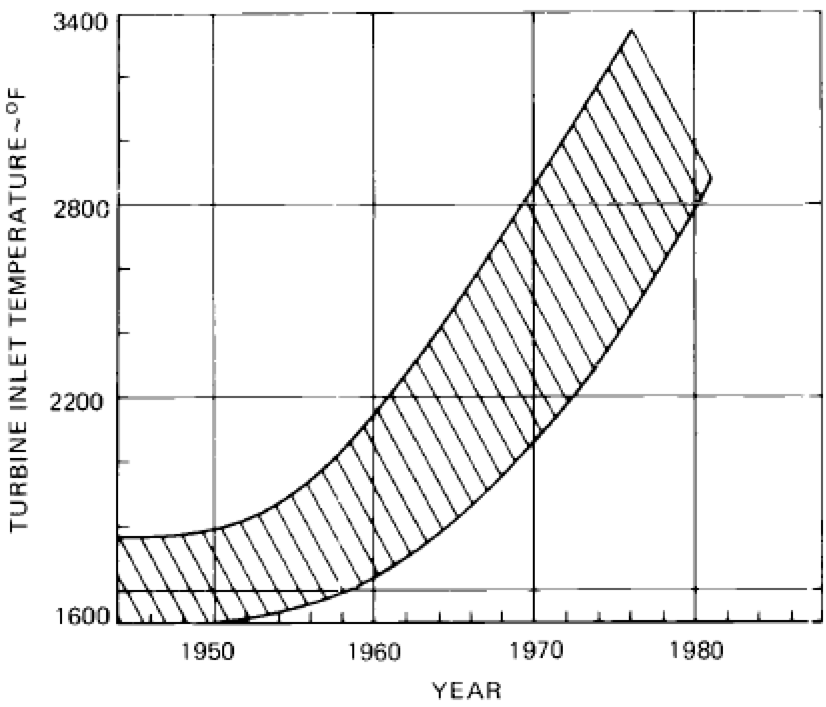


Figure 1.1: Turbine inlet temperature history and projection [1]

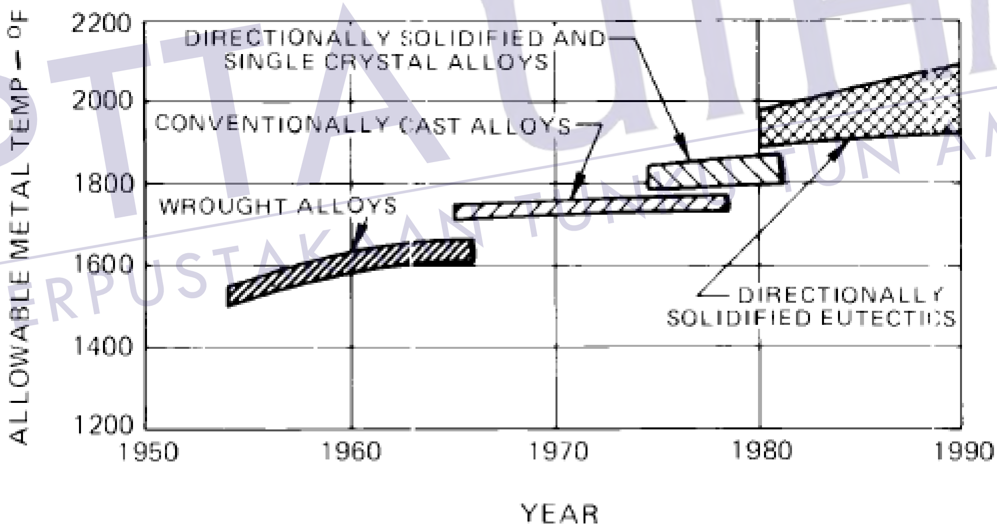


Figure 1.2: Blade material temperature capability history and projection [1]

1.2 Introduction of Gas Turbine

Gas turbine is a rotary engine that extracts energy from fluids motion. At the present time, turbines are among the most powerful machines ever made. Gas turbines are widely used in aircraft and land-based power plants. The major three components of a gas turbine engine are compressor, combustor and turbine as shown in Figure 1.3. The compressor compresses the received air to high pressure, the combustor burns the fuel and produces high pressure and high temperature high velocity gas and the turbine extract the energy from the gas.

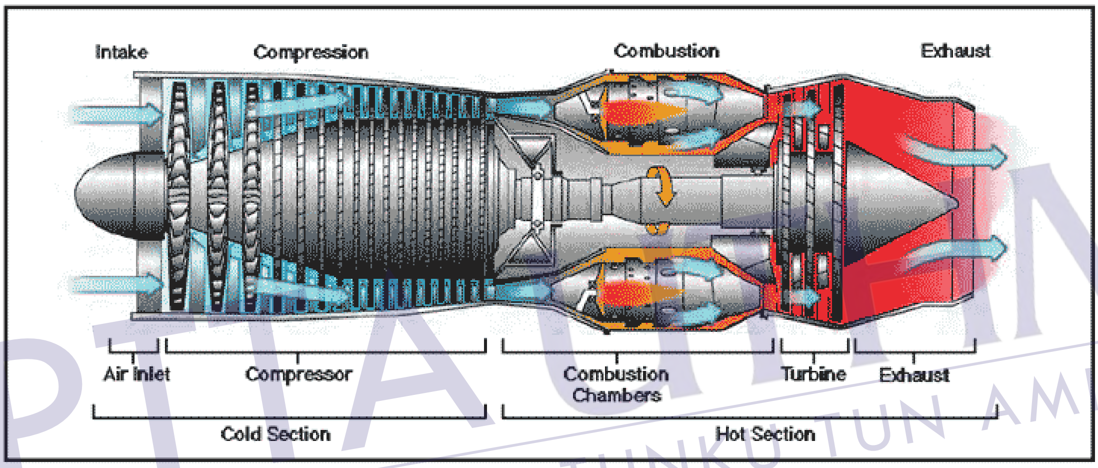


Figure 1.3: Cut-out view of the gas turbine engine [2]

However, due to possible damage to the blade, due to temperature from the combustion chamber is higher than allowable metal temperature for blade. In order to avoid the turbine blades from fail, the blade need extensive cooling. Efficient cooling technique is required in modern gas turbine design due to extremely high turbine inlet temperatures. The present study investigates the effectiveness of film cooling to protect the leading edge surface. As a result a various internal and external cooling techniques were employed to bring down the temperature or the blades bellow its failure point. Usually a combination of internal and external film cooling is employed. One of the most effective and often methods for cooling the blade is known as film cooling technique.

The simplified of turbine blade with film cooling holes is shown in Figure 1.4 [3]. In general, Air is bled from the compressor, sent directly to channels inside the blades and vanes, and injected to the exterior surface through and array of small holes then is injected through holes at locations of leading edge, side surfaces, and trailing edge as shown in figure 1.5 [4]. The complete cooling process is a combination of external film cooling and internal convective cooling.

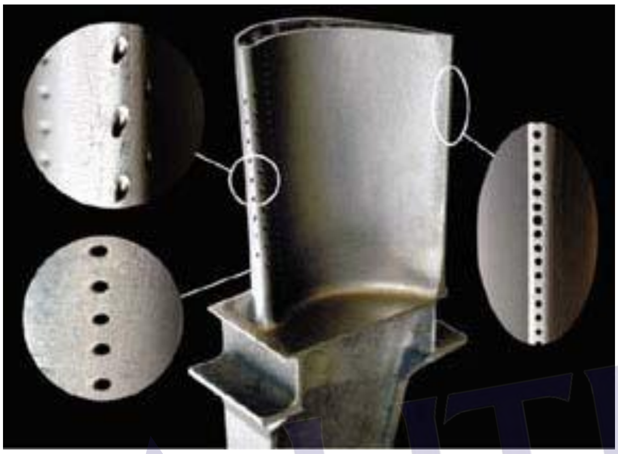


Figure 1.4: Film-cooling holes on a turbine blade [3]

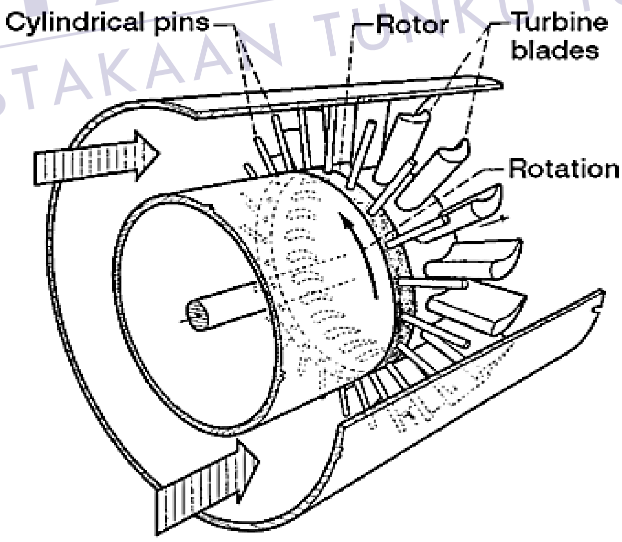


Figure 1.5: *Rotor-wake facility* [4]

1.3 Background of Study

The turbine inlet temperature of modern gas turbine engines has been increased to achieve higher thermal efficiency while the same time the high temperature will cause the materials failure. Therefore, turbine blades, vanes and elements of a combustion chamber must be cooled. In order to overcome the potential problem from the high temperature environment and prevent failure of turbine components, film cooling has been widely employed as an active cooling method. The coolant is extracted from the compressor of the jet engine.

Gas turbine blades are cooled internally and externally. Internal cooling is achieves with the coolant passes through the plenum inside the blade and extract the heat from their surface. External cooling is also known as film cooling, coolant is injected through discrete holes or slot to provide a coolant film, which protect the outside surface blade from the hot temperature, this technique avoidance of direct contact between the blade surface and hot mainstream temperature, thus protecting the turbine component from failure. However, excessive use of coolant can reduce efficiency of entire system. Thus, many investigations have been conducted to understand the physical phenomena regarding the film cooling process and to find better film-hole configurations that can provide better protection with less amount of coolant.

This study is aimed to investigate the effects of the difference depth of trench at the exiting coolant holes and blowing ratio on the leading edge region film cooling effectiveness turbine blade from cylinder in crossflow. Another objective of this study is applying CFD technique on a cylinder in crossflow in order to determine film cooling effectiveness distributions. Present investigation will perform at a single mainstream Reynolds number based on film-hole cylinder diameter of 8,550 at four different coolants to mainstream blowing ratio of 1.0, 1.25, 1.5 and 2.0.

1.4 Problem Statement

Thermal efficiency of gas turbine engines can be efficiently improved by rising the turbine inlet temperature. High efficiency demand higher operating temperature. Thus the turbine blade will extended exposed to the high temperature gases that cause gas turbine engine risk to failure. On the other hand, these high operative temperature affect the durability of the blade, therefore to prevent damage to the blades, a variety of cooling techniques have been developed. The active cooling is essential for the high operating system to maintain and decrease the high temperature while maintaining the temperature within safe operating. Thus by applying a concept of film cooling effectiveness its can avoid the blades from fail or defect. This study is focus on investigate the effect of differences depth of trench holes at the leading edge. Trench holes were form when blades are coated with thermal barrier coating (TBC) layers. The film holes performance and behavior will be different for the trench holes compared to standard cylindrical holes that are flush with the surface. The trench width and depth depend on the mask region and the thickness of the TBC layer. 3D computational fluid dynamics simulation CFD using FLUENT software will be perform to determine the jet-mainstream interactions to better understand the film effectiveness distributions.

1.5 Significant of Study

The motivation behind this study is to understand the concept of the trench effect on film cooling in the leading edge of the turbine blade. The effectiveness and phenomena of mainstream flow through the leading edge is observed in simulation software.

1.6 Objective of Study

The numerical prediction using FLUENT was performed to determine the jet mainstream interactions to better understand the interaction between the ejected coolant and also the surface film effectiveness distribution. The main interest of this research study is to simulate the film cooling in leading edge of turbine blade. The main objectives are as follows:

i. To determine the film effectiveness enhancement due to differences depth of trench which are Case A (0.10mm), Case B (0.28mm) and Case C (0.51mm). Each case simulate under four different blowing ratio which are 1.0, 1.25, 1.5 and 2.0 with single mainstream Reynolds number 8550.

1.7 Scope of Study

The scope of this study is focus on simulation of film cooling in the leading edge region of a turbine blade. The scopes of this study are as follows:

i. Study the blowing ratio effect at BR 1.0, 1.25, 1.5 and 2.0.
ii. Study differrence depth of trench which are 0.10mm,0.28mm, 0.51mm .
iii. Model design by SolidWorks.
iv. CFD is carried out in 3D using FLUENT sofware.
v. Trench effect on film cooling effectiveness from a cylinder in crossflow will be simulated.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

In the aims to produce a higher efficiency turbine engines, the need to improve performance by increasing the inlet gas temperature without shortening the components' lifespan. Thus, a number of studies have focused on developing the best methods to cooling the turbine blade has been done. Film cooling has been extensively studied over the past decades. A majority of the studies have been done on a flat surface.

2.2 Film Cooling Concept

Advanced gas turbine engines run at high temperatures around (1200-1400C) to get better thermal efficiency and power output [5]. As the turbine inlet temperature increases, the heat transferred to the blades in the turbine also increases. The level and variation in the temperature within the blade material (which causes thermal stresses) must be limited to avoid failure to the turbine blades. The operating temperatures extremely high above the permissible metal temperatures need to be cooled to avoid the blade from failure. The blades are cooled by extracted air from the compressor of the engine this technique is called film cooling.

Nowadays, various cooling techniques are embedded to bring down the temperature of the blade material below its melting point to avoid failure to the turbine blades. For an example, Figure 2.1 showed the basic concept of cooling system to the turbines blades. The basic idea to cooling the internal turbine blades, the cold air is bypassed from the compressor and passed through the hollow passages inside the turbine blade [6]. However for the external cooling concept, the bypassed air is exited out through small holes at discrete locations of the turbine blade. This cold air creates a protective layer that saves the turbine blade from the hot temperature.

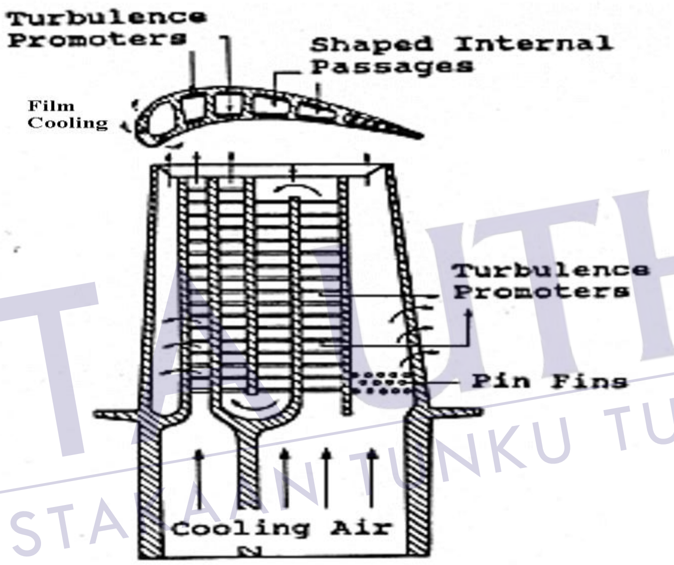


Figure 2.1: Cooling concepts of a modern multi-pass turbine blade [6]

Turbine airfoil surfaces, shrouds, blade tips, and endwalls are all cooled by using discrete-hole film cooling. A typical cooled airfoil is shown in Figure 2.2 [7]. The figure shows the range of locations where coolant is injected into mainstream from inside the airfoil through discrete holes. The advantages of this technique is, it protects the airfoil surface from the hot temperature directly, compared to internal cooling techniques that eliminate heat from the inside surface. This technique also can removes heat from the blade surface by internal convection.

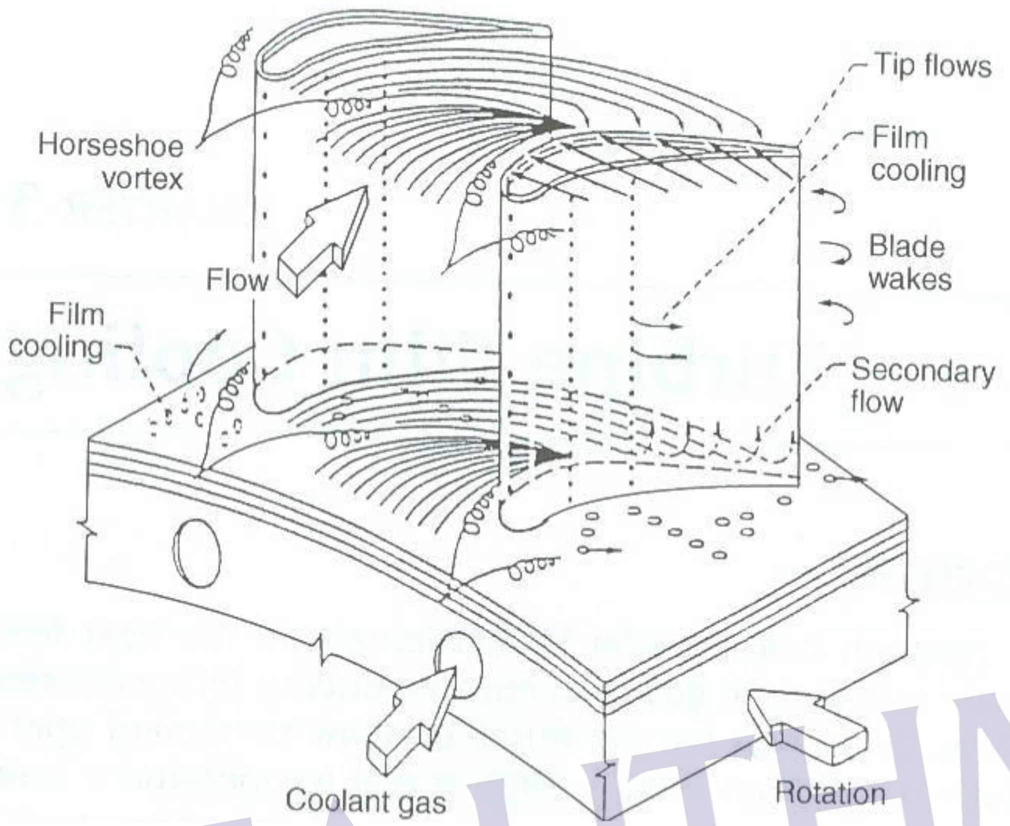


Figure 2.2: A typical cooled airfoil [7]

2.3 Film Cooling Working Principle

The working principle of film cooling is sketched in Figure 2.3. Cooler air from the compressor is injected near the blade surface (through holes or slots) [8]. Coolant air is placed over the airfoil, which serves to insulate the airfoil from the hot turbine gases. Because the coolant mixes with the turbine gases, the film is not a very effective method of cooling in itself. However, when combined with convective cooling from the inside of the airfoil, it is a very effective method of cooling airfoils [1].

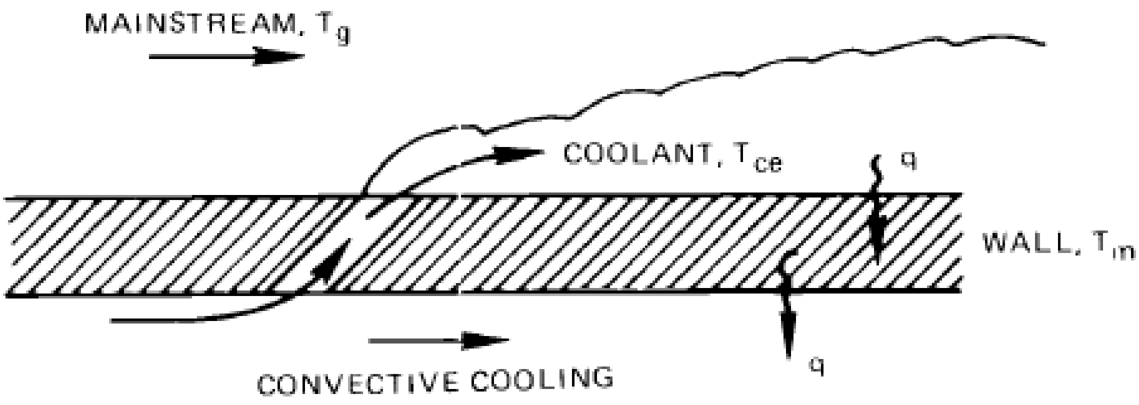


Figure 2.3: Working principle of film cooling [1]

2.4 Film Cooling and Previous Research

Flat surface film cooling has been used long time ago for research purpose. The effectiveness characteristics with lateral injection were investigated by Goldstein et al. [9]. They were investigated the effectiveness of single hole of the inclination angle of 15 and 35 deg. The result shows the effect of lateral injection is to widen the temperature field and decrease the peak effectiveness for the blowing ratio of 0.5. However, for the higher blowing ratios, the lateral injection increases both the width of the temperature field and the peak film cooling effectiveness [9].

Mehendale investigated the influence of high mainstream turbulence on leading edge film cooling effectiveness and heat transfer coefficient. The orientation angle was 90 deg. The results indicated that the film effectiveness decreases with increasing blowing ratio [10]. Goldstein and Yoshida investigated the influence of a laminar and turbulent boundary layer of the crossflow on a laminar and turbulent jet injected through cylindrical inclined holes [11]. From their observed the turbulent jet gives a better cooling effectiveness compared to the laminar at the same blowing ratio.

Mustapha Benabed1 et al. studied the comparative cooling holes geometry and the effects on film cooling effectiveness. All simulations are conducted for the same density ratio of 1.0 and the same inlet plenum pressure [12]. Figure 2.4 shows the six cooling holes geometry configurations which will called: (1) a cylindrical film hole, (2) a shaped film hole, (3) a uniform film slot, (4) a convergent film slot, (5) a crescent film hole, and (6) a trenched film hole. They were found that the comparison of the computational and experimental results was satisfactory on the suction side and on a major part of the pressure side.

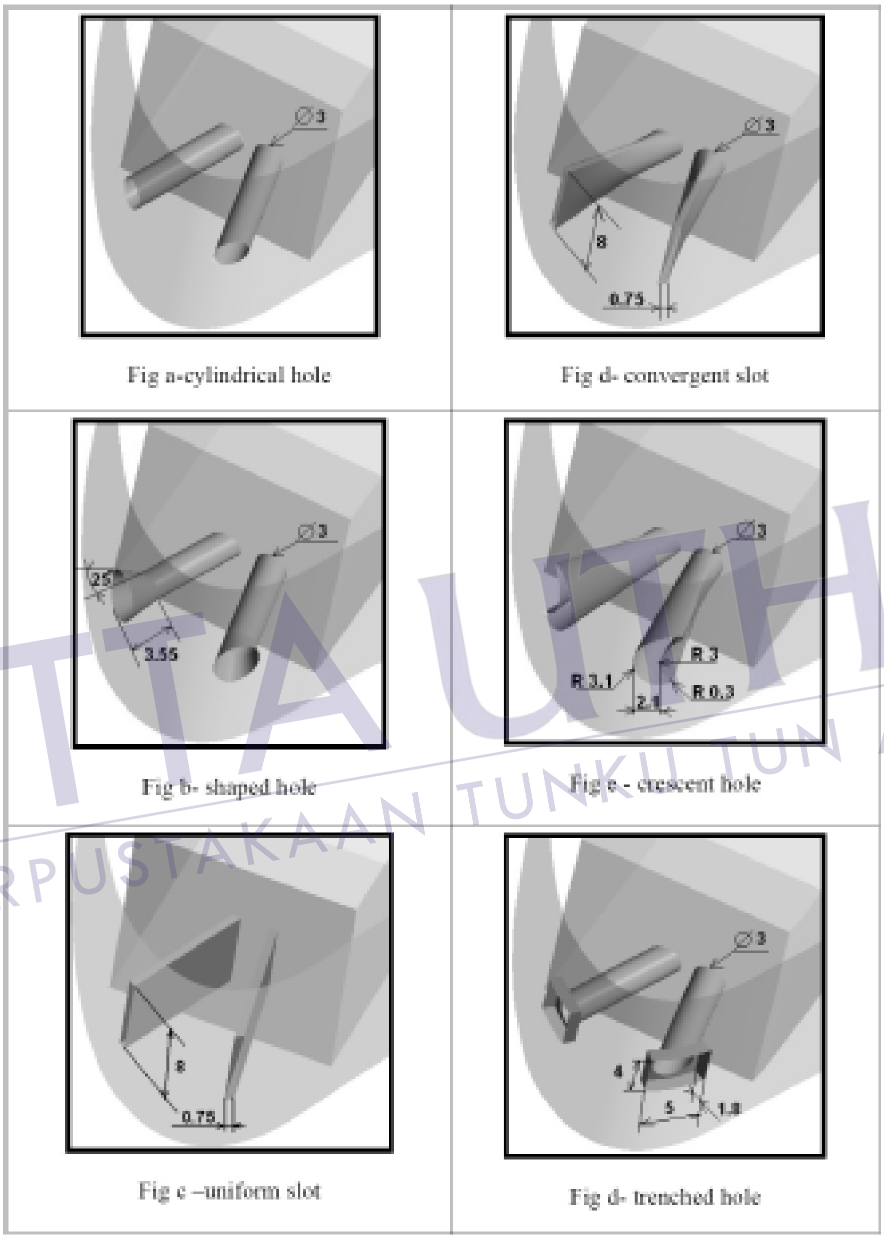


Figure 2.4: Solid model for different film cooling configurations [12]

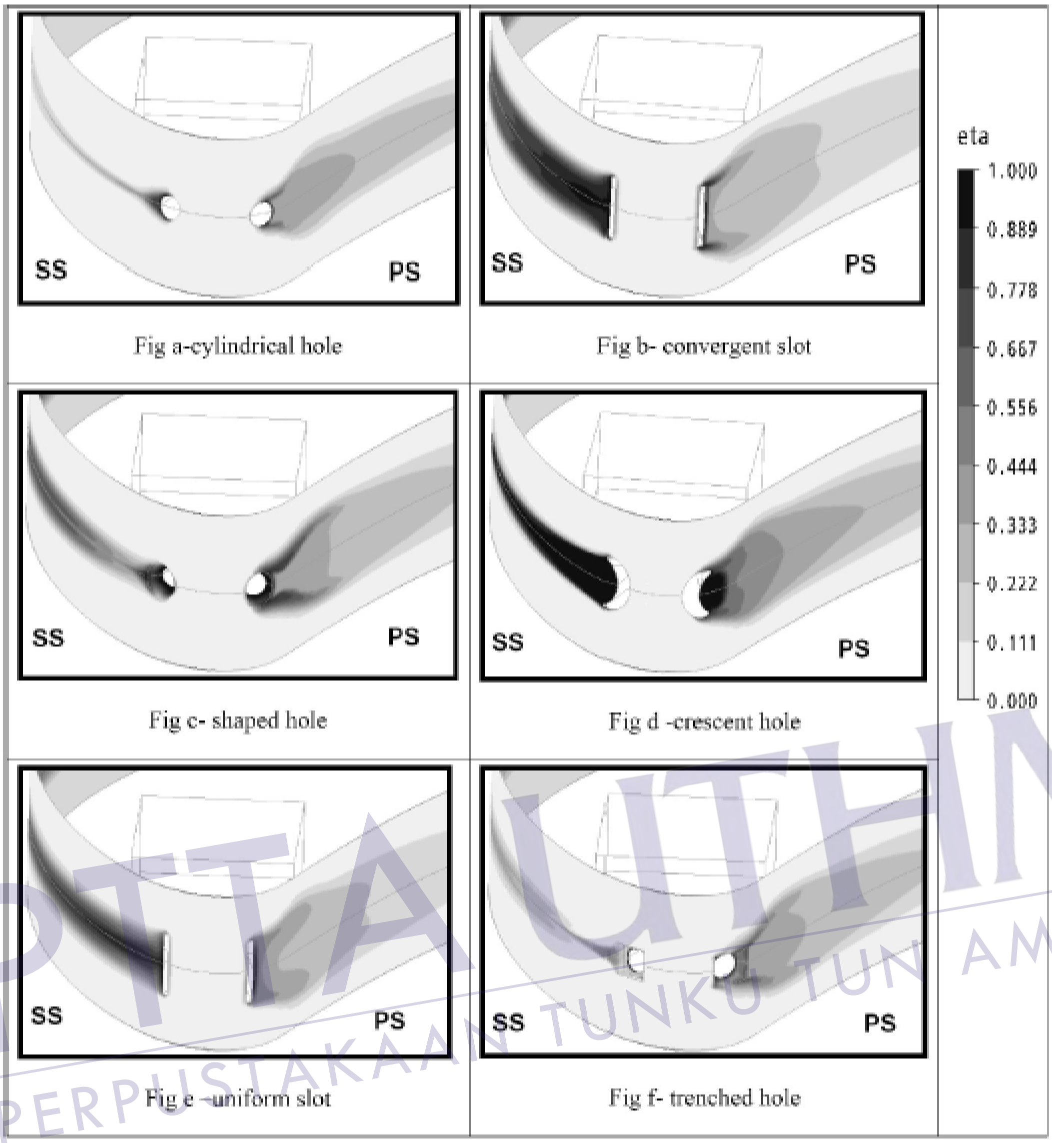


Figure 2.5: Leading edge Film cooling effectiveness contours (midplane) [12]

The entire new five configurations then compared to cylindrical holes, all the five new configurations provide an increase of film effectiveness (Figure 2.6). They investigated that at the SS (suction side) region, the maximum enhancement is registered for the convergent slot and the minimum is for the trenchant slot while at the PS (pressure side) region, the maximum is for the crescent slot and the minimum is for the uniform slot [12].

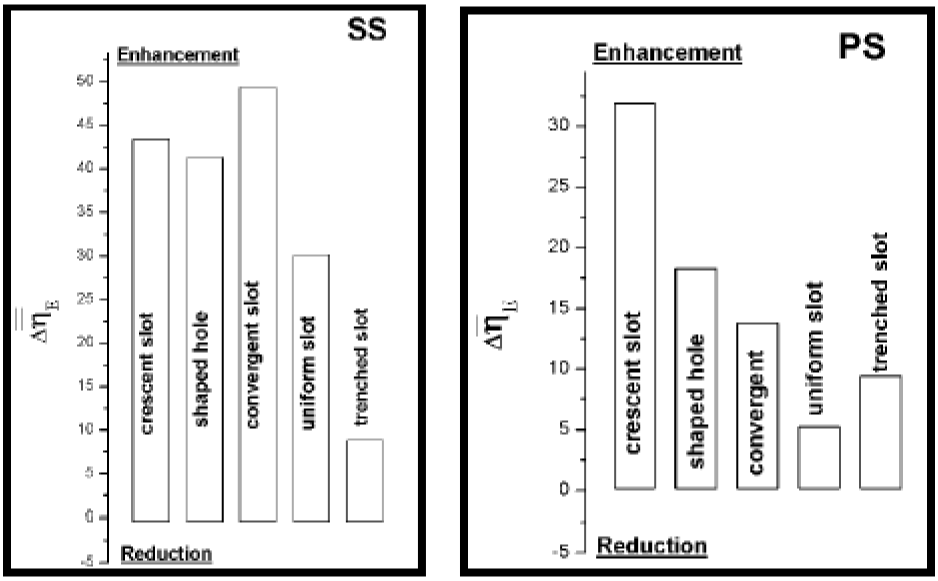


Figure 2.6: Percent enhancement in area averaged film cooling effectiveness for different hole configuration. [12]

Baldauf et al. were investigated the film cooling effectiveness using flat and smooth surface for a baseline geometry cylindrical holes spaced 3*d* apart and inclined 30º to the surface and aligned in the flow [13]. The Results for a range of blowing ratios are presented in figure 2.7. The blowing ratio, *BR,* is the ratio of the coolant mass flux to the mainstream mass flux and is defined as follows:

$$BR = \frac{\rho_c V_c}{\rho_\infty V_\infty}$$

Where, ρc and $\rho\infty$ are the coolant and mainstream density, respectively, and Uc and $U\infty$ are the coolant and mainstream velocity, respectively.

They investigated that the level of film cooling effectiveness (η) increases systematically with an increase in *BR* until *BR* = 0.6, but for *BR* ≥ 0.85, the peak level of η begins to decrease, and the position of the peak moves downstream [13]. Baldauf et al. observed that initial increase in η with increasing BR is expected due to the greater mass flow of coolant and the decrease in η for BR ≥ 0.85 is due to the coolant jet separating from the surface [13].

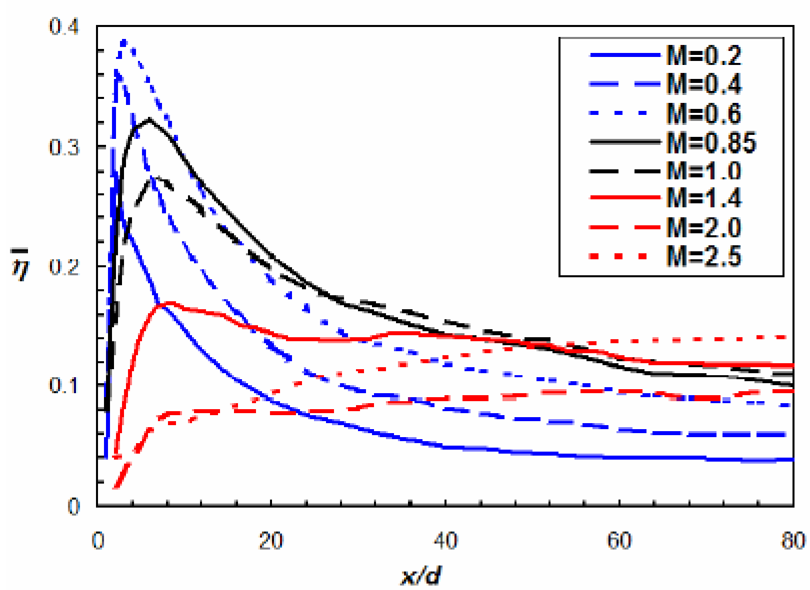


Figure 2.7: Distributions of η for varying blowing ratios presented as a function of the *x/Mse* parameter[13]

David G. Bogard said improved film effectiveness can be achieved if the exit of the hole is expanded so that coolant is slowed through a diffuser. He said there are two advantages for such a "shaped hole" which are the coolant exit velocity is reduced and a broader jet cross-section is presented to the mainstream flow. Both these characteristics will reduce the tendency for the coolant jet to separate. This results in good film effectiveness levels for shaped holes at very high blowing ratios [14].

Other factor that can effect to the film cooling performance is inclination of the holes that connected with the plenum. Based on Yuen and Martinez-Botas investigated the adiabatic effectiveness by means of liquid crystal thermography. They reported there were three angles (30^o, $60\,^o$ and 90^o) have been tested. The result shows that, angle of 30^o shows the best cooling characteristics [15]. It has been reported that the more effective region.

Ligrani et al. investigated the effects of compound angle injection for a single row and two staggered rows of holes. They reported that compound angle injection significantly improved film-cooling protection compared to the simple angle hole keeping all other parameters constant [16]. D. G. Bogard and K.A. Thole investigated turbine film cooling; they reported here are a number of mainstream factors that can affect film cooling performance including approach boundary layers, turbulence levels, Mach number, unsteadiness, and rotation [17]. Because of the very high levels of mainstream turbulence exiting the combustor and entering the turbine section, turbulence levels have the largest effect on film cooling performance [14]. High mainstream turbulence levels degrade film cooling performance by increasing heat transfer coefficients and generally decreasing film effectiveness.

Looking for better film cooling technique, Lu et al. investigated the effect of slot exit area and edge shape on film effectiveness measurements made on a flat plate. They found that a straight edge exit performed the best at a blowing ratio of M=1.0, whereas a ramped exit enhanced the adiabatic effectiveness levels at lower blowing ratios [18].

2.5 Conclusion

As a conclusion, there are a lot of factors that should be considered to increase film cooling effectiveness, such as inclination of the holes that connected with the plenum. Based on Yuen and Martinez-Botas, they reported that there were three angles (30^o, 60^o and 90^o) have been tested. At angle 30^o the result shows the best cooling characteristics [15]. With the objective to look for a better film cooling technique, Lu et al. investigated the effect of slot exit area and edge shape on film effectiveness measurements made on a flat plate. They found that a straight edge exit performed the best at a blowing ratio of *BR*=1.0, whereas a ramped exit enhanced the adiabatic effectiveness levels at lower blowing ratios [18]. Baldauf et al. observed that initial increase in η with increasing BR is expected due to the greater mass flow of coolant and the decrease in η for BR ≥ 0.85 is due to the coolant jet separating from the surface [13]. David G. Bogard said improved film effectiveness can be achieved if the exit of the hole is expanded so that coolant is slowed through a diffuser. He said there are two advantages for such a "shaped hole" which are the coolant exit velocity is reduced and a broader jet cross-section is presented to the mainstream flow. Both these characteristics will reduce the tendency for the coolant jet to separate. This results in good film effectiveness levels for shaped holes at very high blowing ratios [14].

CHAPTER III

METHODOLOGY

3.1. Introduction

This chapter will discuss the method that will be applied to ensure the objective and scope of this project could be achieved. Thus, all work must follow the step and schedule provided. This chapter presented the model, the boundary conditions and assumption behind the model. All the relevant information is gathered through literature review.

The main goal this study is focuses on heat transfer study at leading edge turbine blade. The point this study is to investigate the effect of difference type and dimension of trench to the film cooling effectiveness.

3.2 Flow Chart

Figure 3.1 shows the in a flow chart for investigation. All the work was planned to accomplish this project smoothly

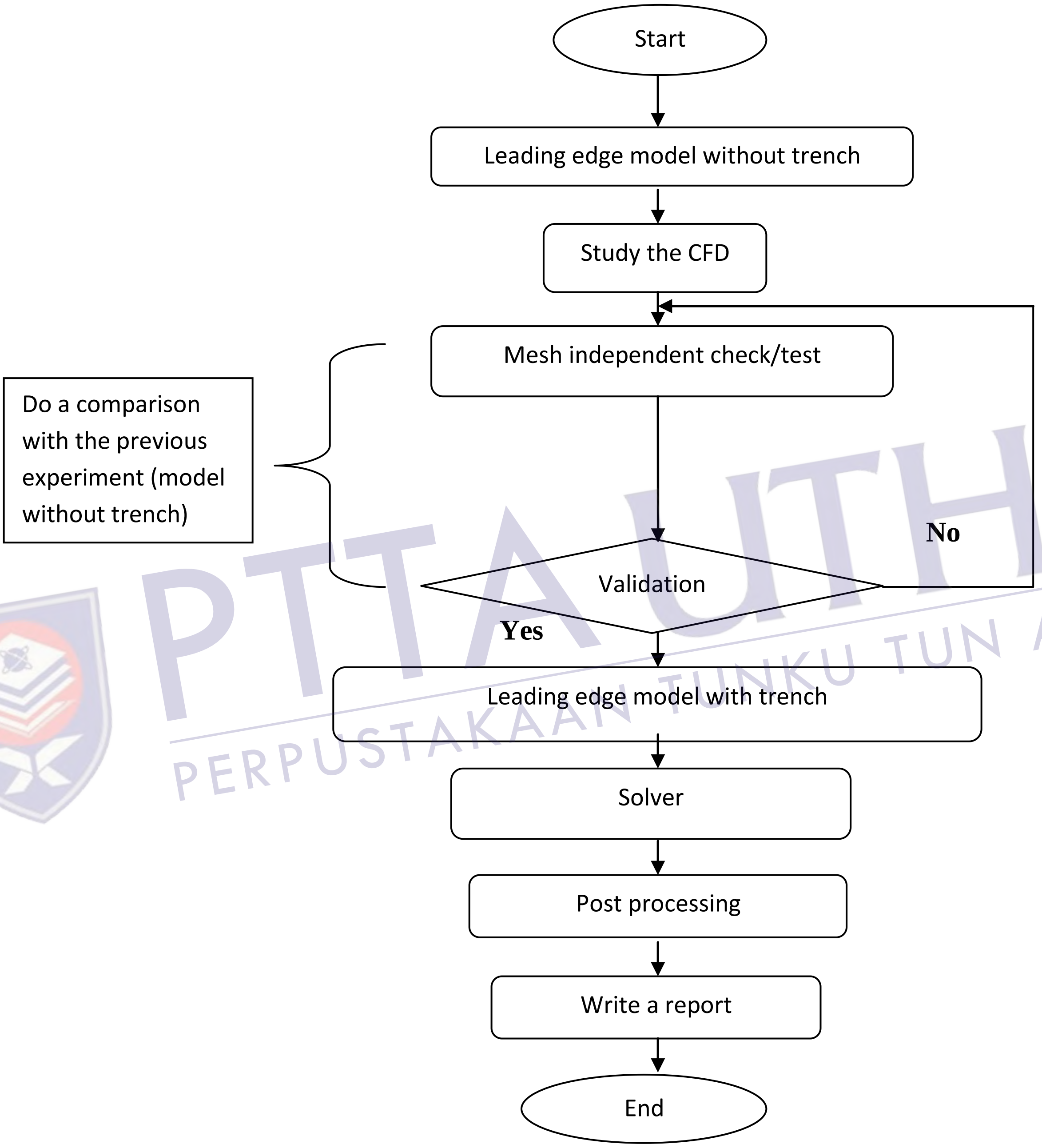


Figure 3.1: Methodology flow chart

3.3 Geometry and Grid Details

First stage SolidWorks uses to draw the film cooling hole of leading edge. Figure 3.2 shows the computational domain of semi-cylindrical leading edge model with a flat after-body in physical 3D geometry. The computational domain consists of a main area, cooling holes, and a secondary flow plenum. The model has span wise length of 62.4mm. Plenum was placed within the cylindrical wall of 80mm diameter (D=10d) and there are three rows of film cooling holes arranged in a staggered fashion. The diameter of each hole is 8mm (d=8mm) and the angle of each cooling holes to the y-axis is 30 degrees. The inclination angle of holes is 30 degrees relative to the spanwise direction. Figure 3.3 show the schematic for the leading edge and Figure 3.4 show the separation angle between the hole 1 (row 1) and hole 2 (row 2) in the x-z plane is 30 degrees and the separation angle between hole 2 (row 2) and hole 3 (row 3) in the x-z plane is 35 degrees. The pitch between the holes is 31 mm (3.86d).

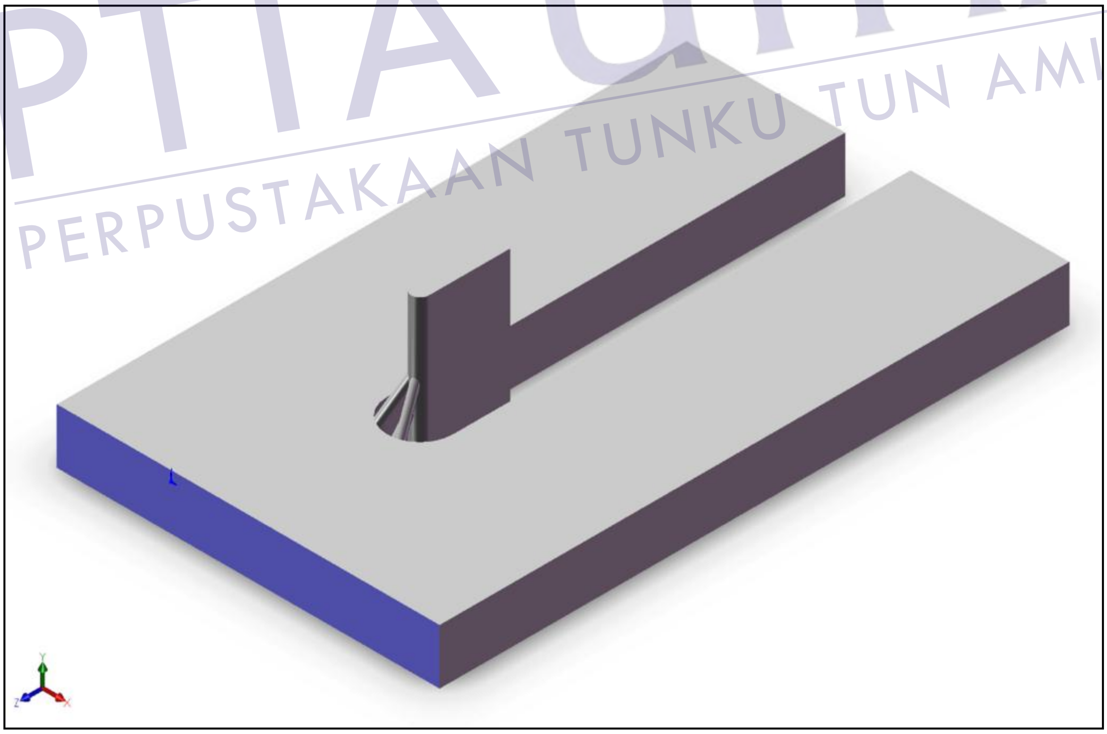


Figure 3.2: Leading edge model

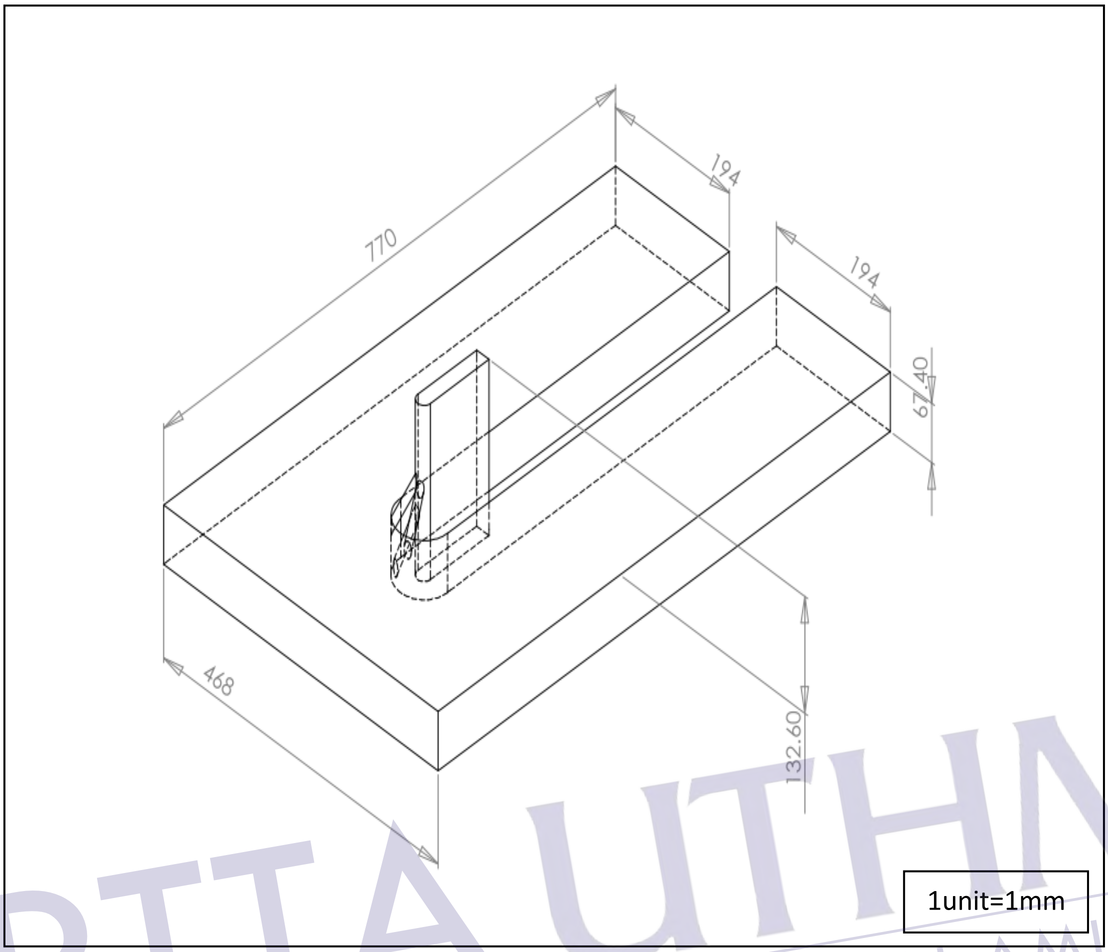
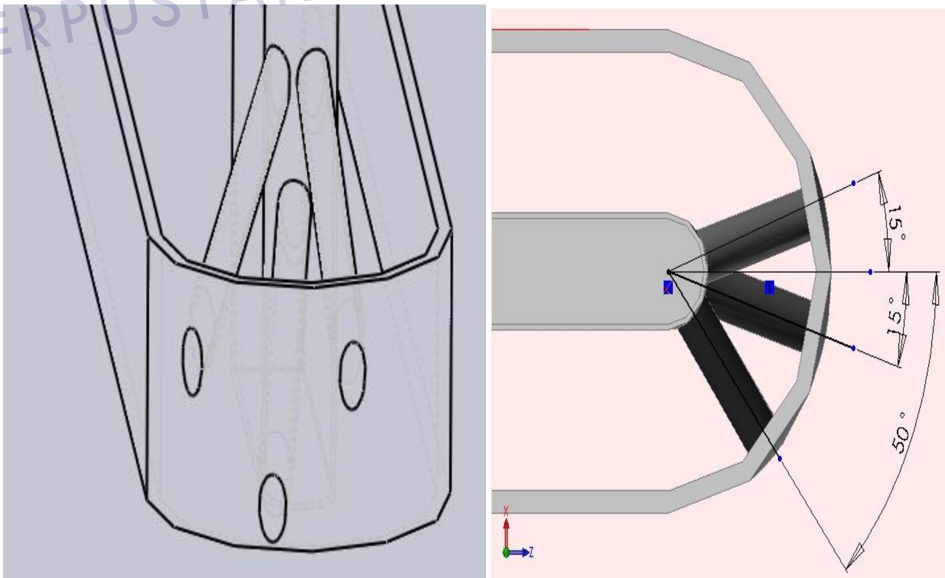


Figure 3.3: Schematic for the leading edge without trench



Font view of the leading edge   Top view of the leading edge

Figure 3.4: Plenum angle

3.4 Computational Fluid Dynamics (CFD)

Computational Fluid Dynamics or CFD is the analysis of systems involving fluid flow, heat transfer and associated phenomena such as chemical reactions by means of computer-based simulation. CFD studies are performed to understand a deeper insight into the flow field that responsible for observed coolant jet characteristic with the mainstream. FLUENT is used to simulate film cooling for trenches leading edge and to validate the result. Then, the result is compare to the previous study.

3.5 Boundary condition

In the computational domain, boundary conditions are set at the domain. Mainstream conditions were maintained the same for all cases. Coolant velocity magnitude is change when altered the blowing ratio for each cases. At the inlet holes, the coolant temperature was set at 321 K and the mainstream temperature was set at 291 K show in Table 3.1. Reynolds number based on the mainstream velocity and the coolant holes diameter, Re_m is 8550. Figure 3.5 show the setup to simulate the process. Four different blowing ratios 0.25, 0.5, 0.75, 1.0, are considered for simulations. For the mainstream and coolant jet velocity inlet, inflow conditions were prescribed at the mainstream and plenum inlet planes. Standard total temperature value and inlet velocity were used at the mainstream inlet with flow normal to the inlet plane. The plenum inlet mass flow rate was adjusted to produce the blowing ratio desired.

Table 3.1: Boundary conditions and numerical setup

Item	Physical Properties
General Condition	Steady state Incompressible Non radiation
Turbulence Model	k-ω SST Model

Boundary Condition		
Inlet	Mainstream temperature (K)	291
	Coolant (K)	321
	Mainstream inlet velocity (m/s)	15.955

x

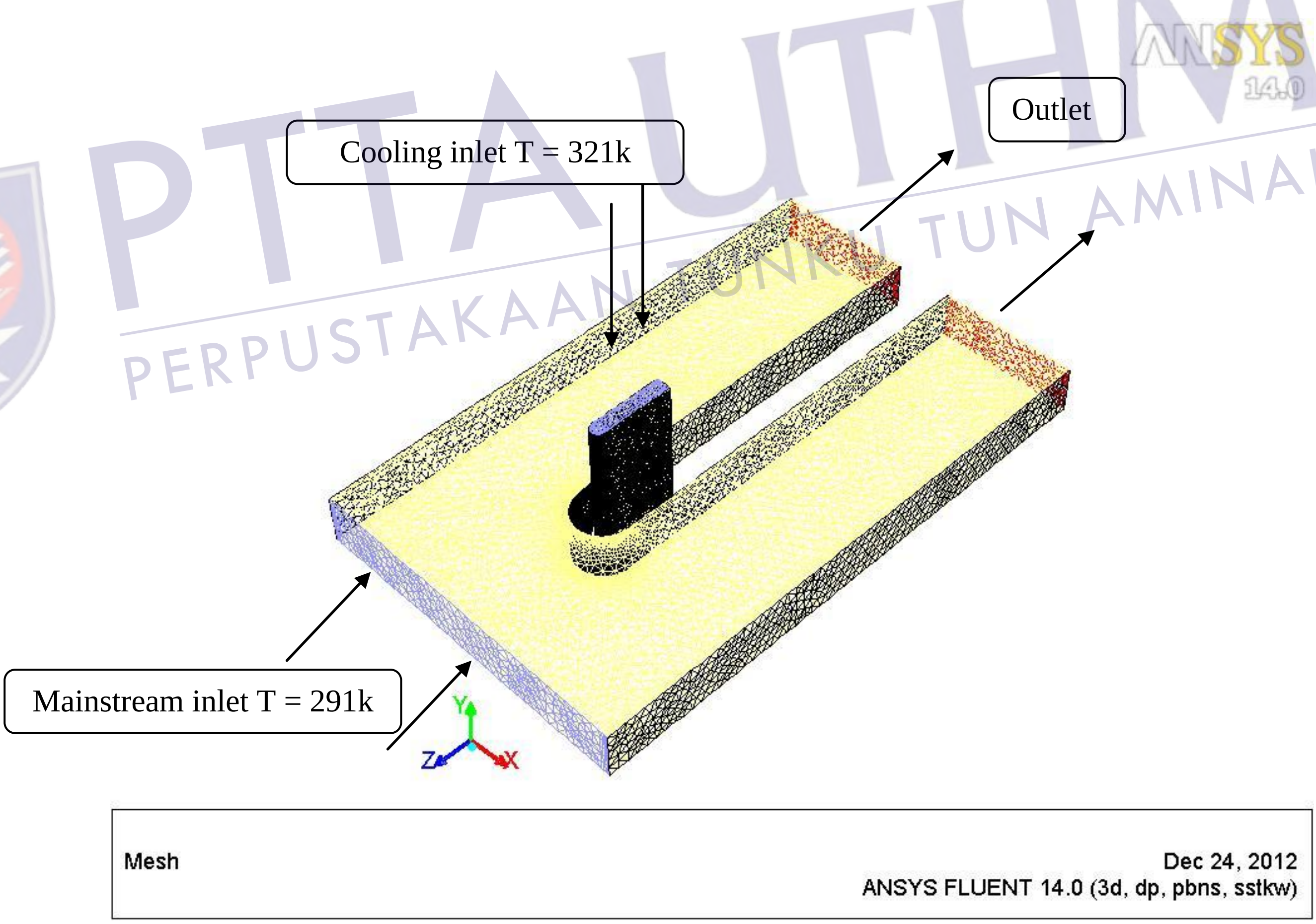
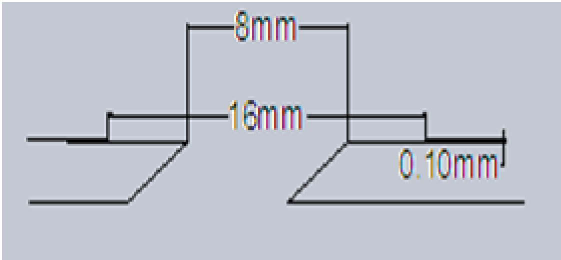


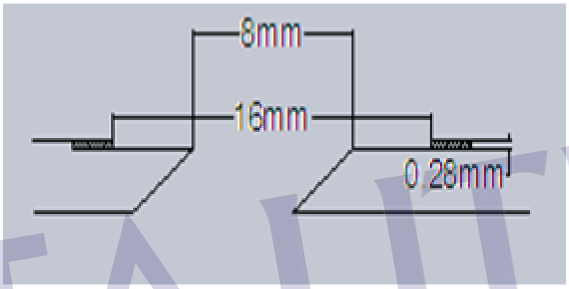
Figure 3.5: Boundary condition for film cooling effectiveness leading edge

3.6 Difference Trench Cases

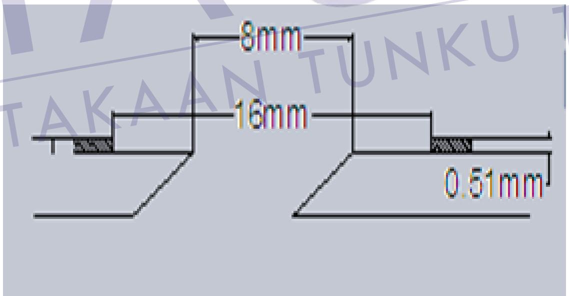
There are three difference of depth trench will be examine. Figure 3.6 show the case to be examined. This trench was embedded at coolant holes exit.



Case A



Case B



Case C

Figure 3.6: Illustrate three difference cases of trench

REFFERENCES

[1] Mikio Su, General Electric Company, Cincinnati, Ohio(Formerly with United Technologies Research Center, East Hartford, Connecticut)

[2] http://www.free-online-private-pilot-ground-school.com/turbine-engines.html

[3] Suman Mishra (2008). "*Single-Hole Film Cooling on a Turbine-Blade Leading-Edge Model*" Master of Science, University of Cincinnati

[4] Heidmann, J.D. (1995). "*A Numerical Study of the Effect of Wake Passing on Turbine Blade Film Cooling"*. AIAA Paper 95-3044 (Also NASA TM-107077).

[5] Je-Chin Han & Srinath Ekkad "*Recent Development in Turbine Blade Film Cooling*" Turbine Heat Transfer Laboratory, Mechanical Engineering Department, Texas A&M University, College Station, TX 77843-3123, USA.

[6] Goldstein, R.J. (1971). "*Film Cooling*" In Advancement in Heat Transfer. Academic Press, New York, Vol.7, pp321-379

[7] Ekkad, S. V., Ou, S., & Rivir, R. B., (2006). "*Effect of Jet pulsation and duty cycle on film cooling from a single jet on a leading edge model*", Journal of Turbomachinery, Vol. 128., pp. 564-571.

[8] Ekkad, S. V., Han, J. C., and Du, H., (1998). "*Detailed film cooling measurements on a cylindrical leading edge model. effect of free-stream turbulence and coolant density*". Journal of Turbomachinery. Vol. 120. pp. 799 – 807.

[9] Goldstein, R. J., Eckert, E. R. G., Eriksen, V. L., and Ramsey, J. W. (1970) "*Film Cooling Following Injection Through Inclined Circular Tubes*," Israel Journal of Technology, Vol. 8, No. 1–2, pp. 145–154.

[10] Mehendale, A.B., Han, J.C. and Ou, S (1991). "*Influence of High Mainstream Turbulence on Leading Edge Heat Transfer,"* ASME Journal of Heat Transfer. Vol. 113. November .pp. 843-850.

[11] Goldstein, R. J., Yoshida, T. (1982). "*The Infuence of a Laminar Boundary Layer and Laminar Injection on Film Cooling Performance* ". ASME J. of Heat Transfer, vol.104, pp.355-362.

[12] Mustapha Benabed, Abbès AzzI and B A Jubran. "*A comparative study of the film cooling hole configuration effects on the leading edge of asymmetrical turbine*." Laboratoire de Mécanique Appliquée, Faculté de Génie-Mécanique, Université des Sciences et de la Technologie d Oran, B.P. 1505 El-Mnouar, Oran, Algeria

[13] S. Baldauf, M. Scheurlen, A. Schulz, and S. Wittig (2002) "*Correlation of Film-Cooling Effectiveness from Thermographic Measurements at Enginelike Conditions*" Journal of Turbomachinery 124. pg: 686-698.

[14] David G. Bogard. Mechanical Engineering Department University of Texas at Austin Austin, TX 78712

[15] Yuen, C. H. N., Martinez-Botas, R. F. (2003). "*Film cooling characteristics of a single round hole at various streamwise angles in a cross°ow Part II: heat transfer coeficients*". *Int. J. Heat and Mass Transfer,* vol.46, pp.237-249.

[16] Ligrani, P. M., Wigle, J. M. & Jackson, S.W. (1994). "*Film-Cooling From Holes with Compound Angle Orientations: Part 2-Results Downstream of a Single Row of Holes with 6d Spanwise Spacing*," ASME Journal of Heat Transfer Vol. 116. No. 2. pp. 353-362.

[17] D. G. Bogard and K.A. Thole (2006). "*Gas Turbine Film Cooling*," accepted AIAA Journal of Propulsion and Power.

[18] Lu, Y., Nasir, H., and Ekkad, S. V., 2005, "*Film-Cooling From a Row of Holes Embedded in Transverse Slots*," ASME Paper No. GT2005-68598.

[19] S. Hamidon, S. Eiji, F. Ken-ichi, T. Toshihiko, W. Kazunori. (2009). "*Numerical Study on Flat Plate and Leading Edge Film Cooling*". ASME